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ACCURACY ASSESSMENT OF TDRSS-BASED TOPEX/POSEIDON ORBIT DETERMINATION*

D. H. Oza, D. T. Bolvin, C. M. Cox, and M. V. Samii
Computer Sciences Corporation, Lanham-Seabrook, Maryland, 20706 USA

C. E. Doll

National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, Maryland, 20771 USA

ABSTRACT

Orbit determination results are obtained for the Ocean Topography Experiment (TOPEX)/Poseidon spacecraft by the Goddard Space Flight Center (GSFC) Flight Dynamics Division (FDD) using a batch-least-squares estimator available in the Goddard Trajectory Determination System (GTDS) to process Tracking and Data Relay Satellite (TDRS) System (TDRSS) measurements. The GTDS orbit solutions are compared with the definitive Precision Orbit Determination (POD) orbit solutions. The root-mean-square (RMS) solution difference in the radial component is 28 centimeters.

INTRODUCTION

This paper assesses the TOPEX/Poseidon orbit determination accuracy of the TDRSS-based orbit solutions using an operational batch-least-squares system within the GSFC FDD. TDRSS and the Bilateration Ranging Transponder System (BRTS) are described in detail in a companion paper /1/. The TDRSS-based orbit solutions are compared with the high-precision orbit solutions obtained by the GSFC Space Geodesy Branch using laser and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) tracking measurements.

The accuracy requirements on the Space Geodesy Branch orbit determination solutions, which are used to analyze the sea surface height measurements obtained by the TOPEX/Poseidon radar altimeter, are extremely stringent. The definitive orbit determination requirements for the TOPEX/Poseidon mission science data include a maximum 13-centimeter (1σ) radial position error. The availability of the high-accuracy independent orbit determination solutions generated by the Space Geodesy Branch provides a unique opportunity to evaluate the accuracy of the orbit determination systems used by the FDD for operational navigation and analysis support.

ANALYSIS PROCEDURES

This section describes the analysis procedures used in this study and provides a description of the tracking measurements and orbit determination and modeling methods.

Tracking Measurement

The TOPEX/Poseidon spacecraft was launched on an Ariane 42P expendable launch vehicle in August 1992. In October 1992, maneuvers were completed that moved the spacecraft into its operational orbit, which is circular with an inclination of 66 degrees, an altitude of 1336 kilometers, a period of 112 minutes, and a 10-day ground track repeat period. The time period chosen for this study was from 00:00 hours coordinated universal time (UTC) on 7 November 1992 through 21:33 hours UTC on 11 November 1992, which corresponds to the latter portion of the fifth 10-day ground track repeat cycle, hereafter referred to as Cycle 5. This timeframe was chosen because this period was well characterized through previous analyses /2/.

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Tracking measurements from TDRSS were used in GTDS to estimate the TOPEX and TDRS definitive ephemerides. The GTDS orbit solutions were obtained using two-way range and one-way return and two-way Doppler data from TDRSS in addition to two-way range data from BRTS. The tracking consisted of an average of 10 passes of one-way return Doppler measurements and 11 passes of two-way range and Doppler measurements per day, with the average pass lasting 40 minutes.

GTDS batch-least-squares estimation. The batch-least-squares estimation algorithm used by GTDS for this analysis is the same as that used for operational navigation support of the TOPEX/Poseidon mission by the GSFC FDD. The modeling and state estimation parameters used for this analysis were improved to provide more accurate results and to take advantage of techniques not currently in operational use. Specifically, the TOPEX/Poseidon state space was expanded to include estimation of the coefficient of solar radiation pressure, in addition to multiple along-track thrust parameters that were intended to compensate for an anomalous acceleration acting on the spacecraft. Analysis of the operational TOPEX/Poseidon orbit solutions has indicated the presence of an unmodeled spacecraft body-fixed force with a day-to-day variability. Analysis performed by the Jet Propulsion Laboratory (JPL) has indicated that the unmodeled force is dependent on the angle between the orbit plane and the Sun /3/.

TDRS orbit determination procedure. TDRS spacecraft trajectories were estimated simultaneously with TOPEX/Poseidon using both BRTS range and TOPEX/Poseidon two-way range and two-way and one-way return Doppler data to determine the best possible TDRS trajectories for use in the TOPEX/Poseidon-only batch estimation. The modeling, data types, and other orbit determination options used for the TDRSs and TOPEX/Poseidon in the simultaneous solution are presented in Table 2 of /2/. The data span chosen was 5 days, with one thrust correction factor per day. The simultaneous TDRS/TOPEX solution arcs were selected to avoid all maneuvers and angular momentum unloads, where possible, while maintaining the longest possible data spans. In addition, central angle editing was used to mitigate the effects of ionospheric refraction on the TDRS-to-TOPEX/Poseidon tracking link. The central angle chosen was designed to eliminate all data below the TOPEX/Poseidon local horizon.

Numerous transponder delay corrections were necessary to resolve biases between the BRTS and TOPEX/Poseidon range measurement types in the simultaneous solutions. These transponder delays included the individual transponder delays for each BRTS ground transponder and a transponder delay on each TDRS. In addition, a TOPEX/Poseidon spacecraft transponder delay correction value was applied to reduce the effects of ranging calibration errors on the TDRS and TOPEX/Poseidon orbit solutions. Application of at least a single BRTS transponder delay is necessary to prevent the orbit solutions from being ill-determined. Measurement residual analysis, supported by comparison with a Precision Orbit Ephemeris (POE) indicated that the default White Sands Ground Terminal (WSGT) BRTS transponder delays provided optimal TOPEX/Poseidon estimation. Estimation of the Alice Springs, Australia, BRTS transponder delay was found to have little impact on the TOPEX/Poseidon estimation accuracy. The applied TOPEX/Poseidon transponder delay correction was modeled as a range bias and was determined based on an auxiliary solution in which BRTS and TOPEX/Poseidon range measurement biases were estimated instead of the BRTS and TDRS transponder delays.

TOPEX/Poseidon orbit determination procedure. After the TDRS trajectories were estimated in the simultaneous solution, they were used to compute a TOPEX/Poseidon-only solution based on the one-way and two-way Doppler data only. This was done to minimize the effect of TOPEX/Poseidon range data bias modeling errors on the TOPEX/Poseidon trajectory. The span of this solution was only 4 days, and it was selected to reduce the dynamical modeling errors and to simplify the thrust estimation parameter selection. Force modeling for the TOPEX/Poseidon-only solution is the same as that used for the simultaneous solutions with TDRS, with the exception that only two thrust correction factors were estimated for the 4-day data span.

RESULTS AND DISCUSSION

The GTDS TOPEX ephemeris, spanning the latter portion of Cycle 5, was compared with the Cycle 5 POE. This GTDS ephemeris, which corresponds to the TOPEX-only solution, is 4 days long and spans the period 00:00 hours UTC on 7 November 1992 through 00:00 hours UTC on 11 November 1992. The RMS position differences between the GTDS TOPEX ephemeris and the Cycle 5 POE is 1.1 meter, with a maximum difference of 2.0 meters.

Figure 1 shows the radial, cross-track, and along-track position differences for the separate TOPEX solution on 9 November 1992. The maximum radial difference is 0.5 meter, while the maximum cross-track difference is 1.2 meters. The maximum along-track difference, which is the largest of the three components, is about 2.0 meters. The along-track RMS difference is 0.89 meters, while the RMS differences in the radial and cross-track components are 0.28 meter and 0.56 meter, respectively.

Some of the difference in the along-track component is likely due to differences in the modeling of the along-track accelerations. The POEs estimate a daily once-per-revolution along-track acceleration, consisting of two estimated parameters per day, and a daily constant along-track acceleration to accurately model the effects of the anomalous spacecraft forces as well as atmospheric drag perturbations. The GTDS TOPEX-only solution, however, estimates only two thrust correction factors to characterize the along-track forces. Similarly, the POEs estimate a daily once-per-revolution cross-track acceleration, consisting of two solved-for parameters per day, to characterize the cross-track accelerations, while the GTDS solutions estimate no cross-track accelerations due to software limitations. Some differences can, in part, also be attributed to the differences in the modeling of the attitude changes resulting from the yaw-steering feature. These would affect both the measurement modeling and the atmospheric drag and solar radiation pressure force modeling. The POEs model the instantaneous changes in the spacecraft cross-sectional areas for drag and solar radiation pressure evaluation resulting from the yaw steering. The separate GTDS TOPEX solution uses the variable mean area model, which provides mean orbital values of the drag and solar radiation pressure cross-sectional areas. The truncation of the Joint Gravity Model-2 (JGM-2) geopotential model from 70×70 to 50×50 contributes no more than a few centimeters error in the orbit solutions at the altitude of TOPEX/Poseidon.

GTDS orbit determination solutions have been obtained using state vectors from the Cycle 5 POE as the measurements. This form of orbit determination solution eliminates all measurement and TDRS spacecraft dynamical force modeling, thereby making it possible to estimate the amount of error resulting from the dynamical modeling used in GTDS for TOPEX/Poseidon. The solution span corresponds to the same 4-day span used for the TOPEX/Poseidon-only orbit determination solution, which was presented earlier, and used POE state vectors at 12-minute intervals. The root-sum-square (RSS) position differences between this special solution and the Cycle 5 POE are shown in Figure 2. The mean RSS position difference is 0.4 meter, with a maximum difference of 1.1 meters. The maximum radial, along-track, and cross-track differences are 0.4 meter, 0.9 meter, and 1.0 meters, respectively. The average component differences are all zero. The differences reflect the force modeling differences between the GTDS dynamical force modeling and the Cycle 5 POE.

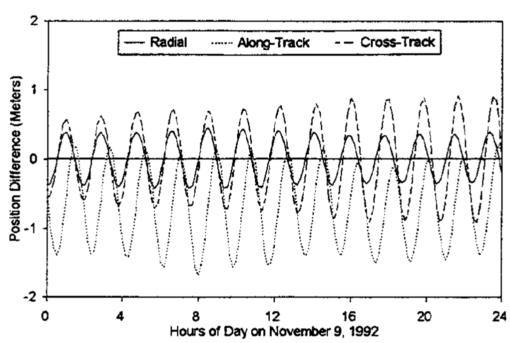

Fig. 1. Position differences by component between POE and GTDS ephemerides for November 9, 1992

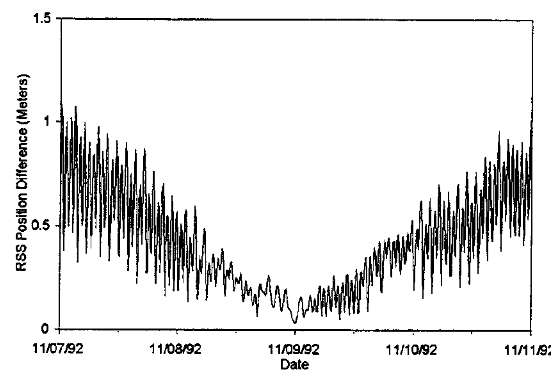

Fig. 2. Comparison of special GTDS solution with the POE

The validity of the secular trends in the GTDS dynamic modeling differences was verified by performing GTDS solutions for arc lengths of 1 day through 10 days, with increasing arc lengths by a day each for Cycle 5. The characteristics of the comparison of the 10 solutions with the POEs did not change from the short (1-day) arc length to the long (10-day) arc length. This demonstrated that the effects of dynamical mismodeling are small compared with the other errors. Corresponding covariance analysis solutions with the same tracking schedules as the 10 GTDS solutions supported the trend of the GTDS solutions.

It is important to note that TDRSS tracking does not have a requirement to yield orbit solutions with accuracy comparable to laser-tracked orbit solutions. However, a major objective of this work is to assess the achievable TDRSS orbit determination accuracy.

CONCLUSIONS

This study analyzed the TDRSS-user orbit determination accuracy using a batch-least-squares estimation method. Estimated orbits obtained were compared to the POEs.

These solutions compare with the POEs at less than 2 meters in maximum total position difference. The radial component compares at a 28-centimeter RMS difference, less than three times the 13-centimeter (1σ) POE accuracy requirement. Dynamical TOPEX/Poseidon modeling errors in GTDS have been shown to cause a maximum of 1 meter of the observed error in the solutions. Given the observed residuals and the known level of dynamical mismodeling in the current GTDS solutions, it can be stated that the TDRSS tracking measurement data have sufficient quality to support orbit determination to levels better than 2 meters in accuracy, provided issues of sufficient tracking coverage and accurate orbit determination modeling are addressed.

The reduction of the differences, as compared with an earlier analysis /4/ was the direct result of the use of the improved TDRS orbits obtained from the TOPEX/TDRS simultaneous solutions. This demonstrates that the treatment of the relay orbit determination has a significant impact on high-accuracy orbit determination in the TDRSS environment.

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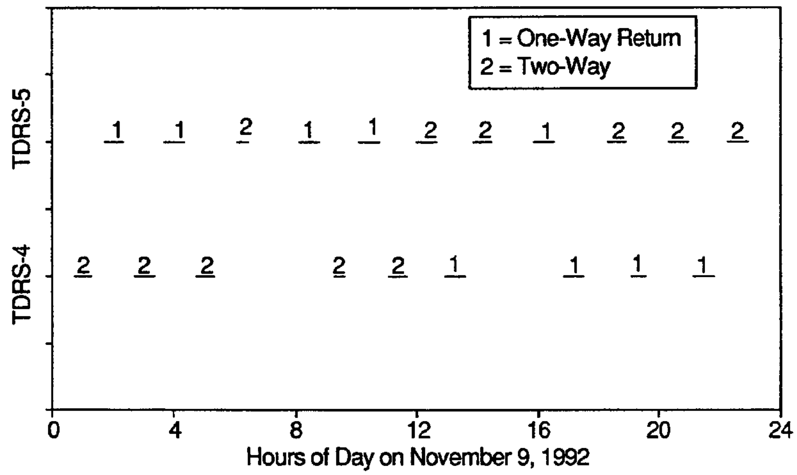
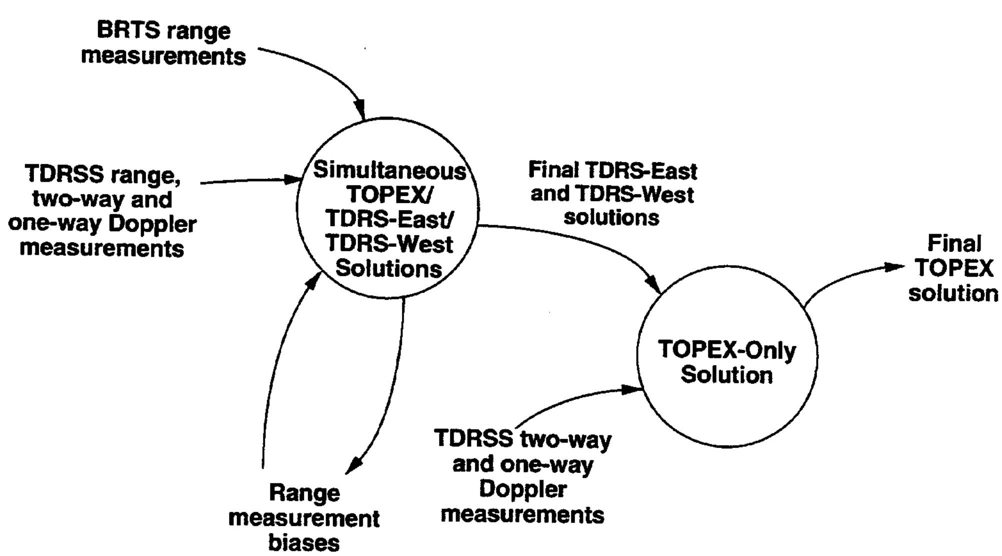
Typical TDRSS Tracking Data for TOPEX/Poseidon



Batch-Least-Squares Orbit Determination Processing



POE and GTDS Force Models

Force Model	POE Solution	GTDS Solution
Geopotential model	70 x 70 Joint Gravity Model-2 (JGM-2)	50 x 50 JGM-2
Atmospheric density model	Drag Temperature Model (DTM)	Jacchia-Roberts Model
Satellite area model	Box/wing model	Variable Mean Area (VMA) Model
Anomalous force modeling	One per revolution along-track and one per revolution cross-track solved for	Constant along-track thrust scaling parameter
Ionospheric refraction correction: Ground-to-spacecraft link Spacecraft-to-spacecraft link	 Not applicable Not applicable	 Yes No
Ocean tides	Yes	No
Earth radiation pressure	Yes	No
Plate motion	Yes	No
User spacecraft antenna offset correction	Yes	Constant radial, along-track, cross-track
Solar radiation pressure	Yes	Yes
Tropospheric refraction correction	Yes	Yes
Polar motion correction	Yes	Yes
Solid Earth tides	Yes	Yes

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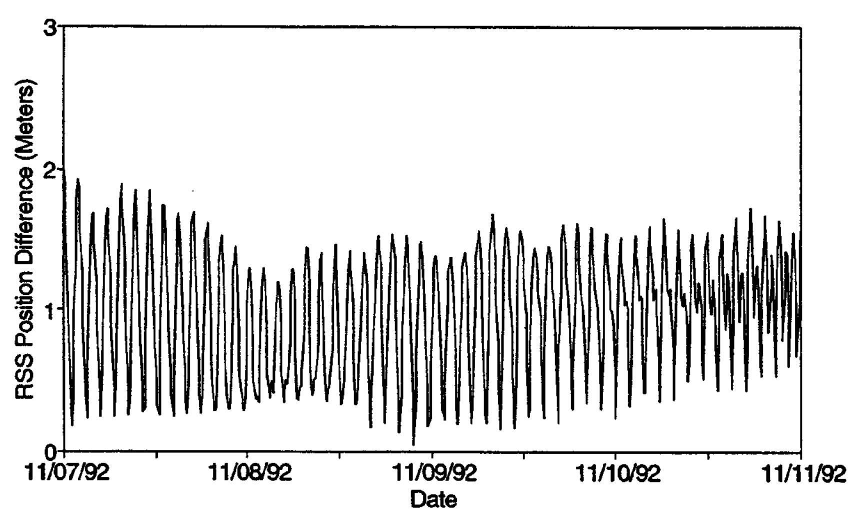
GTDS Ephemeris/POE Comparison Results (1 of 3)

Position Differences Between POE and GTDS TOPEX/Poseidon Ephemeris



RMS Difference: 1.1 meters